ARMY RESEARCH LABORATORY

Application of the Depth-of-Penetration Test Methodology to Characterize Ceramics for Personnel Protection

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Abstract

The depth of penetration (DOP) or thick-backing technique allows the ballistic evaluation and ranking of armor ceramics independent of armor configuration. The test projectile is fired into a ceramic tile backed by a semi-infinite block. The residual penetration into the backing material is measured and compared to the penetration of the projectile into a monolithic block of the backing material. This report adapts this technique to evaluate armor ceramics for personnel protection using the caliber .30 armor-piercing M2 (APM2) and armor-grade aluminum alloy 5083 (Al 5083), MIL-A-46027, as the backing material.

Penetration of the APM2 into monolithic Al 5083 was determined over a range of velocities. Several thicknesses of boron carbide (B_4C), silicon carbide (SiC), and aluminum oxide (Al_2O_3) were tested to determine ballistic performance as a function of ceramic areal density. Projectile cores were recovered and analyzed. Postmortem condition of the cores was correlated to DOP results.

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1. Introduction

The continuing improvement of materials for personnel protection has led to lightweight personnel armor systems that can provide protection from many small-arms rounds. This, in turn, has lead to the development of improved armor-piercing (AP) projectiles to defeat personnel body armor. This has created a situation where it is desirable to provide military personnel with protection against small-arms AP projectiles. The caliber .30 AP M2 (APM2), once considered a vehicle threat, may now be considered a ballistic threat to military personnel.

Currently, the material systems under investigation for personnel protection against this round are ceramic-faced laminates with fiber-reinforced polymeric composites as a backing material. The primary ceramics that research and development have been focused on are aluminum oxide (Al_2O_3), silicon carbide (SiC), and boron carbide (B_4C). This study uses the residual depth of penetration (DOP) method to determine the ballistic efficiency of ceramic materials suitable for personnel protection against the APM2.

The use of DOP experiments has successfully been used to characterize and rank armor ceramics for vehicle protection [1]. These studies involve firing a projectile, usually a 65-g, L/D 10, 91% W long rod penetrator, into a ceramic block backed by semi-infinite steel armor (rolled homogeneous armor [RHA], MIL-A-12560). The residual penetration into the backing plate is then measured and compared to the penetration into a monolithic RHA target with no ceramic front plate. The ballistic performance of the ceramic may then be presented in the form of residual DOP vs. ceramic areal density (AD).

This method, sometimes called the thick-backing technique, has also been used to examine ceramic performance against small-arms AP threats using aluminum backing. Rosenberg et al, [2] looked at two types of Al_2O_3 against caliber .30, caliber .50, and 14.5-mm AP rounds and developed an expression for ballistic efficiency and showed that under proper conditions the efficiency for a material does not vary with material thickness or threat diameter. Rosenberg and Yeshurun [3] showed a correlation between a material's compressive strength and its ballistic

efficiency. Rosenberg, Yeshurun, and Tsaliah [4] examined backing material properties. Woodward and Baxter [5] investigated the influences of test conditions, notably threat material and geometry.

This study determines baseline penetration of the APM2 into monolithic aluminum and then determines the ballistic efficiency of several armor-grade ceramics against this threat. A description of the APM2 and mechanical properties of all materials tested are given in the first section. The experimental procedure is described and experimental results from testing of both monolithic aluminum blocks and ceramic-faced aluminum blocks are presented, followed by an analysis of recovered projectiles.

2. Procedure

2.1 Projectile Description. The APM2 is a jacketed, steel-cored, AP round, with a muzzle velocity of 841 m/s (2760 fps). The core of this projectile is made from a steel alloy with a hardness of Rockwell-C 63 that is quite effective in penetrating lightly armored targets. Penetration into metallic armors (Hardness <Rc63) by the APM2 is characterized by rigid-body penetration and plastic deformation of the armor material. The dimensions and components of the APM2 are shown in Figure 1, with a detailed component list in Table 1. The APM2 is used as the projectile in this study, as it is one of more severe small-arms AP threats.

2.2 Backing Material. Armor-grade aluminum alloy 5083-H131 (Al 5083), MIL-A-46027, was chosen as the backing material for this program. This alloy is well characterized, and its ballistic performance well known. Al 5083 backing plates used had a nominal thickness of 3 in. Mechanical properties for this alloy are given in Table 2.

2.3 Ceramic Materials. The ceramics investigated are aluminum oxide, silicon carbide, and boron carbide. The aluminum oxide used was obtained from Coors Ceramic Corporation. It contains nominally 94% pure aluminum oxide and is designated as Al_2O_3-AD94. The silicon carbide and boron carbide were both supplied by Cercom Inc. The mechanical properties for

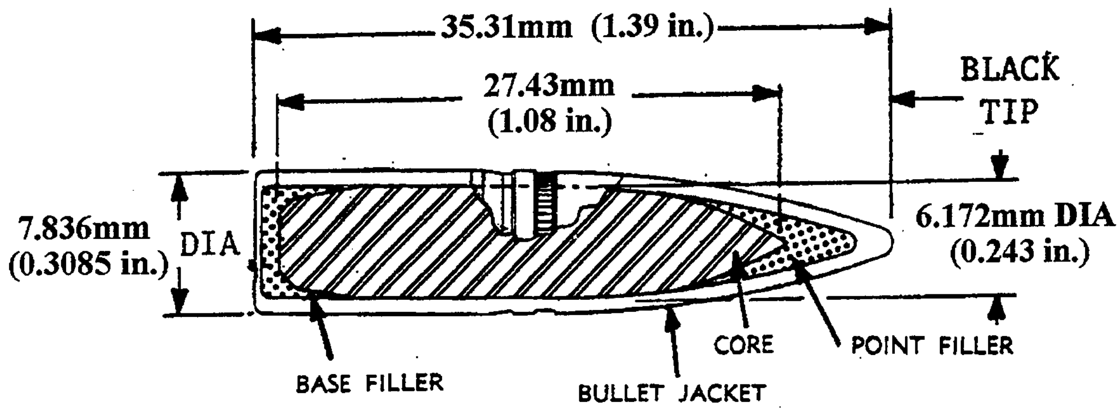

Figure 1. Caliber .30 AP M2.

Table 1. Caliber .30 AP M2 Components

Component	Material	Weight g (gr)
Jacket	Gilding Metal	4.2 (65.0)
Core	Hardened Steel - Rc 63	5.3 (81.0)
Point Filler	Lead	0.8 (12.0)
Base Filler	Lead	0.5 (7.7)
Total Weight		10.8 (165.7)

Table 2. Mechanical Properties for Al 5083

From Laminate Armor for Light Combat Vehicles, MTL TR-86-14 [6]	
Density (g/cm^3)	2.65
Tensile Strength (MPa)	377.1
Yield Strength (MPa)	318.5
Elongation (%)	9.3

these materials are supplied by the materials' manufacturer and are listed in Table 3. In addition to Cercom's standard silicon carbide (SiC-B), a newer product (SiC-N) was also tested on a limited basis.

Table 3. Typical Mechanical Properties for Armor-Grade Ceramics

	Al_2O_3-AD94	SiC-B	B_4C
Density (g/cm^3)	3.70	3.20	2.49
Elastic Modulus (GPa)	303	455	455
Shear Modulus (GPa)	124	195	28.3 195
Longitudinal Wave Velocity (km/s)	9.6	12.3	13.7
Poisson's Ratio	0.21	0.14	0.17
Hardness (kg/mm^2)	1175[a]	2700[b]	3000[b]
Compressive Strength (MPa)	2103	3410	2760

[a] 1000-g Knoop hardness.
[b] 300-g Knoop hardness.

2.4 Ballistic Test Procedure. The testing for this program requires firing the APM2 at velocities ranging from 450 to 900 m/s (1500–2900 fps), with the majority of firings to be at the muzzle velocity for this round, 841 m/s. Velocities are to be ±15 m/s (50 fps) from the specified velocity. All impacts are to be at normal incidence (0° obliquity) with a maximum combined pitch and yaw angle (ϕ) of ±3.00°. The combined pitch and yaw angle is found by using the following equation:

$$\phi = \sqrt{\text{pitch}^2 + \text{yaw}^2} \,. \tag{1}$$

The APM2 was launched from a caliber .306 Mann gun barrel with a twist rate of 1:10 using Hogdon 4895 black powder. This powder enabled accurate prediction of velocity and yaw cycle so that the gun could be properly placed to maintain the required ±3.00° pitch and yaw angle. After test firings to determine powder curves and yaw cycle, the end of the gun muzzle is set approximately 4 m from the target face. Changes in velocity were obtained by varying the weight of the powder charge used.

Projectile velocity and pitch/yaw angles were obtained using flash radiography. Two pairs of 150-keV x-ray heads were placed orthogonal to each other and normal to the projectile flight path. Flash x-rays were taken 40 and 45 cm in front of the target face. A break screen was located 76 cm before the target face to trigger the flash x-rays.

Testing was conducted against both monolithic aluminum (Al 5083) and ceramic-faced aluminum targets. The ceramic-faced targets were prepared by adhering a ceramic tile to an aluminum block using a two-part, 24-hour-cure epoxy. The tile was pressed into the face of the aluminum, forcing the epoxy to flow from between the ceramic and aluminum, leaving a minimal layer of epoxy. All ceramics were tested while backed to nominal 75-mm (3 in)-thick Al 5083. For the ceramic-faced tests, the target was placed in a plywood box in an attempt to contain and recover ceramic fragments and the projectile. A small hole was cut into the front of the box to allow the projectile to pass unobstructed to the target.

The penetration into the aluminum block was measured after testing for both the monolithic and the ceramic-faced targets. Penetration was determined by measuring from the tip of the penetration cavity to the rear surface of the aluminum and subtracting from the measured thickness of the block. This method prevents plastic deformation of the front surface from interfering with accurate measurements. Original measurements were made using three techniques, post-test x-ray of the penetration cavity, thin-rod depth gauge, and direct measurement of cut target blocks. Good correlation of results was obtained using all of these methods, except in the case where projectile or ceramic fragments were embedded in the penetration cavity. Fortunately, these obstructions can be visually identified. This allowed the option of using the method best suited for each target. The method used in obtaining each data point is reported with the results.

3. Test Results

3.1 Penetration Into Monolithic Aluminum. A total of 44 shots were taken to obtain baseline penetration into monolithic Al 5083. As stated earlier, impact velocities ranged from 450–900 m/s. As the ceramic-faced tests were to be at 841 m/s, a greater number of tests were conducted in the 820–900 m/s (2700–2900 fps) range to adequately map penetration performance in this range. At lower velocities (below 600 m/s), difficulty in obtaining acceptable pitch and yaw angles resulted in discounting a number of tests. Results from all monolithic aluminum shots are located in Appendix A. Penetration into monolithic Al 5083 is plotted in Figure 2, and the data have been curve fit with a second order polynomial function:

$$P_{Al\ 5083} = 7.4959 - 8.3612e\text{-}3\ V_S + 6.4995e\text{-}5\ V_S^2, \qquad (2)$$

where, $P_{Al\ 5083}$ is the DOP into Al 5083 in millimeters and V_S is the strike velocity in meters per second. This curve fit shows good correlation to the experimental data and is consistent with APM2 penetration into monolithic aluminum being proportional to the square of the strike velocity (i.e., dependent on the kinetic energy of the round). As equation 2 is derived from an empirical curve fit, it may only be considered valid over the velocity range for the data presented (450–900 m/s).

Postmortem examination of the targets and projectiles indicate that during penetration the jacket and lead filler were stripped from the core, while the hardened steel core remained intact with no permanent deformation. These observations support the earlier assumption of penetration of the steel core by rigid-body penetration with plastic deformation of the aluminum. From equation 2 and Figure 2, it is seen that the penetration of the APM2 into a Al 5083 at muzzle velocity (841 m/s) is 46.4 mm (1.83 in).

3.2 Penetration Into a Ceramic-Faced Target. The test procedure was repeated with a strike velocity of 841 ± 15 m/s for the ceramic-faced targets and the residual penetration measured. Due to variations in projectile velocity, the baseline penetration for each shot varied. Therefore, the performance measure used to evaluate each ceramic was velocity dependent. Using equation 2, the penetration into monolithic aluminum for each shot was calculated based on the actual strike velocity. The ballistic efficiency for each test was then calculated as:

$$\eta = \frac{\rho_{Al\ 5083}(P_{Al\ 5083}(V_S) - P_r)}{\rho_c t_c}, \qquad (4)$$

Where $\rho_{\ Al\ 5083}$ is the aluminum density (2.65 g/cm^3), $P_{Al\ 5083}$ (V_S) is the penetration into monolithic aluminum at the strike velocity, as calculated by equation 2, P_r is the residual penetration into the backing aluminum, ρ_c is the ceramic density, and t_c is the ceramic thickness. Note that $\rho_c t_c$ is also known as the ceramic AD.

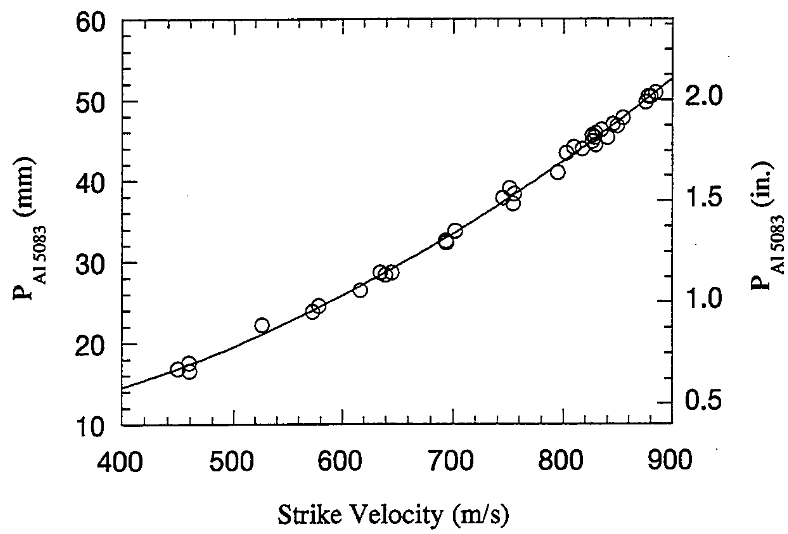

Figure 2. Penetration Into Monolithic Aluminum (Al 5083) vs. Strike Velocity.

The average residual penetration and ballistic efficiency for each type and thickness of ceramic are given in Table 4. To prevent variations in penetration due to strike velocity fluctuations, only tests within the accepted velocity range (841 ±15 m/s) were utilized. Experimental data are presented in Figure 3 as the residual penetration AD (millimeters of residual aluminum penetration × the aluminum density) vs. the AD of the ceramic tile. Also included are curve fit equations for each of the ceramic types. Results for all shots, including measurement technique, are located in Appendix B.

Table 4 and Figure 3 show B_4C having the highest ballistic efficiencies of the three types of ceramic. B_4C is followed by SiC-B, then Al_2O_3-AD94. This relative ranking is consistent with the performance of these ceramics when incorporated into armor systems. Within the limited range of testing conducted, SiC-N shows similar performance to SiC-B. Although B_4C has the higher maximum efficiency, at low ADs, SiC-B has similar or even higher efficiencies. This trend is explained in the next section.

Previous studies [2–5] have shown a linear relationship between ceramic AD and residual penetration; however, those data were limited to the mid and upper ranges of the ceramic AD. Table 4 shows that at low ceramic ADs, the ballistic efficiency for each ceramic is much lower

Table 4. Summary of Residual DOP for Ceramic-Faced Targets

Ceramic	Nominal Ceramic Thickness (mm)	Average Ceramic AD (kg/m^2 [psf])	Shot (s)	Average Residual Penetration (mm [in])	Ballistic Efficiency (η)
B_4C	1.25	3.38 [0.69]	2	40.6 [1.60]	3.54
B_4C	2.50	6.51 [1.33]	3	33.4 [1.32]	5.51
B_4C	3.75	9.65 [1.98]	4	10.1 [0.40]	9.96
B_4C	5.00	12.89 [2.64]	1	0.0 [0.00]	9.53
SiC-B	1.25	4.25 [0.87]	3	41.0 [1.64]	3.02
SiC-B	2.50	8.44 [1.73]	4	26.5 [1.05]	6.19
SiC-B	3.75	12.60 [2.58]	3	6.7 [0.27]	8.35
SiC-B	5.00	16.80 [3.44]	4	0.0 [0.00]	7.35
Al_2O_3-AD94	1.25	4.89 [1.00]	3	41.9 [1.66]	2.29
Al_2O_3-AD94	2.50	9.34 [1.91]	3	38.4 [1.52]	2.23
Al_2O_3-AD94	3.75	14.05 [2.88]	2	22.7 [0.92]	4.35
Al_2O_3-AD94	5.00	18.67 [3.82]	3	6.8 [0.26]	5.66
Al_2O_3-AD94	6.25	23.50 [4.81]	2	0.0 [0.00]	5.21
SiC-N	3.75	12.66 [2.59]	4	7.3 [0.28]	8.21

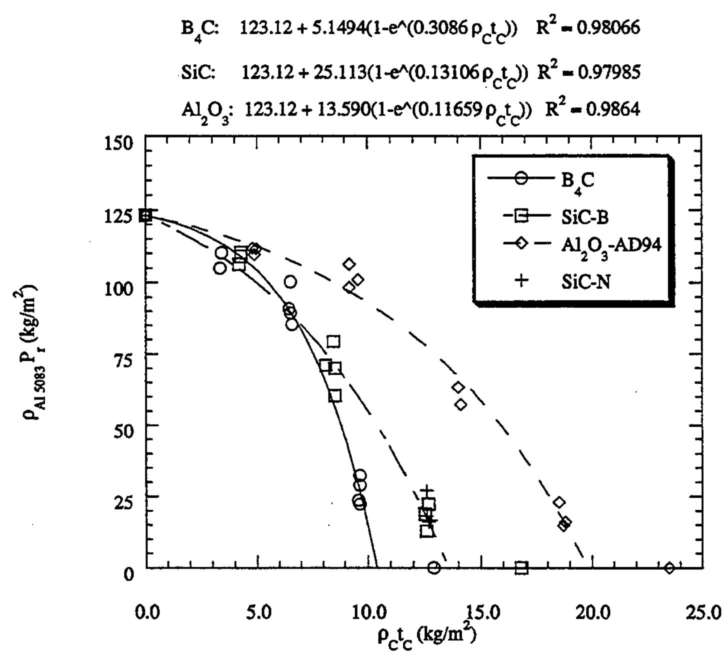

Figure 3. Residual Penetration Areal Density vs. Ceramic Areal Density.

than at higher ADs. This is consistent with the predicted performance curves proposed by Woolsey, Kokidko, and Mariano [1] for situations where the ceramic is overmatched by the projectile. As ceramic AD increases, ballistic efficiency increases until the projectile is defeated in the ceramic tile. The hardened steel core of the APM2 is not defeated by steady-state erosion as are tungsten or softer steel cores; therefore, there is no linear decrease in penetration with increased ceramic AD as seen in previous studies.

When the projectile is defeated in the ceramic tile, there is a drop in ballistic efficiency. The efficiency rating of the ceramic is based on a performance term ($P_{AL\ 5083}\ (V_S) - P_r$) and a weight term ($\rho_c\ t_c$). When the projectile is defeated in the ceramic, the performance term is maximized (no residual into the semi-infinite backing), and any additional increase in ceramic thickness only increases the ceramic AD, without any increase in the performance, thus reducing the ballistic efficiency.

3.3 Postmortem Projectile Analysis. During testing for this study, projectiles and ceramic debris were collected for postmortem examination. The recovered projectile cores were weighted and characterized by the type and extent of damage. Particular attention was paid to the core of this round because during testing, the jacket and lead filler are stripped from the core, as mentioned earlier. During the monolithic aluminum shots, there was no damage to the APM2 core; however, projectile cores recovered from ceramic-faced shots showed varying degrees of damage. Due to the hard and brittle nature of the of the APM2 core, there was no plastic yielding and damage was limited to erosion of the tip or fracture of the core. Accordingly, the recovered cores were classified into the following categories:

(1) Pristine: Core intact, no sign of erosion to the core.
(2) Tip eroded: Core intact, tip shows signs of erosion, but the ogive shape is still noticeable.
(3) Tip fractured: Core fractured in tip area, body intact.
(4) Body fractured: Core fractured in the body.
(5) Body shattered: Core body severely fractured.

Figure 4 shows typical examples of each of these types of core damage. Appendix C contains the data for recovered core weights and conditions. Table 5 lists the condition of recovered projectiles for each ceramic type and thickness tested, along with the number of recovered projectiles in each category.

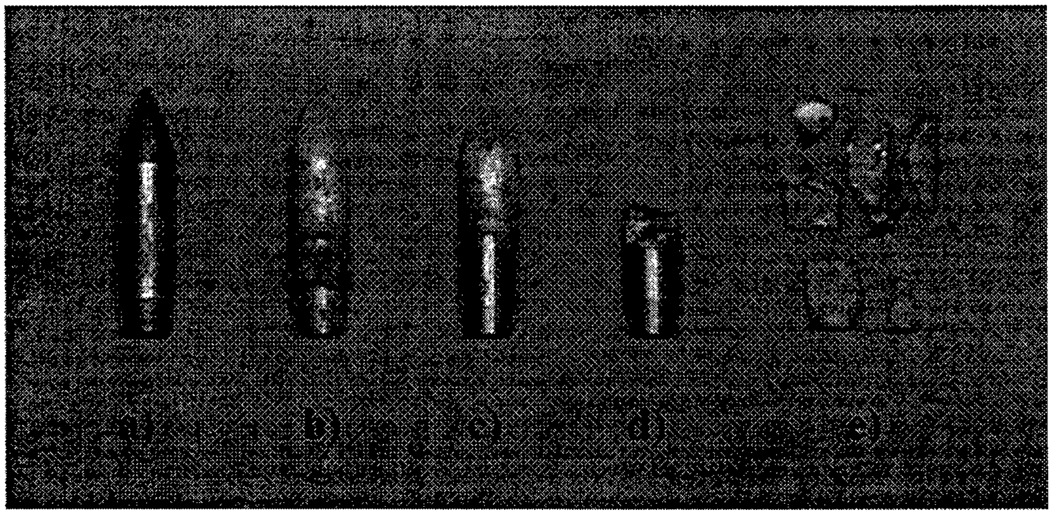

Figure 4. Typical Examples of Core Damage. From Left to Right: a) Pristine, b) Tip Eroded, c) Tip Fractured, d) Body Fractured, and e) Body Shattered.

Postmortem examination of recovered projectiles at low ADs (<5 kg/m^2) showed minimal damage to the projectile core, slight erosion of the tip, allowing substantial residual penetration. Accordingly, these shots had low ballistic efficiencies. As the ceramic thickness increased, projectile damage also increased and residual penetration decreased. Once the body of the projectile core is fractured or shattered, there is a drastic drop in residual penetration. This is consistent with Woodward, who showed that the efficiency of a penetrator into aluminum decreases if the projectile is blunted.

It is noted that the SiC-B causes greater damage to the projectile than the same thickness of B_4C. Al_2O_3-AD94 requires thicker tiles than B_4C and SiC-B to do the same level of damage. This relative ability to damage the projectile follows the compressive strengths for these ceramics, with SiC-B (3410 MPa) ranking above B_4C (2760 MPa) and Al_2O_3 (2103 MPa).

Table 5. Summary of Recovered Projectile Condition by Ceramic and Thickness

Ceramic Thickness (mm)	B_4C	SiC-B	Al_2O_3-AD94
1.25	Tip Eroded (3)	Tip Eroded (1)	Tip Eroded (2)
2.50	Tip Eroded (2) Tip Fractured (1)	Tip Fractured (2)	Tip Eroded (3)
3.75	Tip Fractured (2) Body Fractured (1) Body Shattered (1)	Body Fractured (2) Body Shattered (2)	Tip Fractured (4)
5.00	Body Shattered (1)	Body Fractured (2) Body Shattered (2)	Tip Fractured (2) Body Fractured (1) Body Shattered (1)
6.25	NA	NA	Body Fractured (1) Body Shattered (1)

Although SiC-B does more damage to the projectile, B_4C maintains higher efficiencies due to its lower density. Comparison of recovered projectiles from the SiC-B and SiC-N shows that both types of SiC initiate similar damage to the projectile.

4. Conclusions

This study has shown that the DOP technique can be successfully adapted for use with hardened steel-cored projectiles and to determine the efficiency of thin ceramic materials. Four common armor-grade ceramics have been evaluated. The DOP data for these ceramics correlates with known ballistic data for these ceramics when used in armor systems, namely, that SiC outperforms Al_2O_3-AD94, which, in turn, is outperformed by B_4C. Evaluation of SiC-N shows similar performance to SiC-B.

Analysis of recovered projectile cores shows that insufficient ceramic thickness causes very little damage to the projectile, resulting in low efficiencies. Ceramic efficiency increases with ceramic thickness until the projectile is defeated in the ceramic tile.

Future studies will evaluate the effect of backing material and thickness on the ceramic efficiencies. The effects of various aluminum and composite backings will be studied along with various backing thicknesses. This method is easily adaptable to evaluate other materials for personnel protection, and the data compiled from this study provides a convenient database for future testing and comparison of materials.

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Appendix A:

Ballistic Test Data - Monolithic Aluminum (5083-H131)

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Shot No.	Pitch (°)/Up or Down		Yaw (°)/Left or Right		Total Yaw (°)	Test Velocity (m/s [fps])	Measured Depth of Penetration (DOP) (mm [in])	Measurement Method
2774	1.00	Up	2.00	Right	2.24	884.2 [2901]	50.9 [2.00]	x-ray
2775	1.00	Up	1.25	Right	1.60	880.6 [2889]	50.4 [1.99]	x-ray
2776	1.00	Up	0.25	Right	1.03	887.8 [2880]	50.4 [1.99]	x-ray
2777	1.00	Up	0.00	—	1.00	875.7 [2873]	49.7 [1.96]	x-ray
2778	2.50	Up	0.00	—	2.50	840.3 [2757]	45.4 [1.79]	x-ray
2779	1.00	Up	0.50	Left	1.12	834.5 [2738]	46.3 [1.82]	x-ray
2780	1.50	Up	0.50	Right	1.58	828.1 [2717]	45.4 [1.79]	x-ray
2781	0.00	—	1.00	Right	1.00	829.4 [2721]	45.9 [1.81]	x-ray
2782	0.50	Up	1.50	Left	1.58	809.2 [2655]	44.2 [1.74]	x-ray
2783	0.25	Down	1.00	Right	1.03	826.0 [2710]	45.6 [1.80]	x-ray
2784	0.00	—	0.00	—	0.00	829.1 [2720]	44.4 [1.75]	x-ray
2785	0.25	Down	0.00	—	0.25	826.0 [2710]	44.9 [1.77]	x-ray
2790	0.50	Up	0.25	Right	0.56	854.4 [2803]	47.8 [1.88]	x-ray
2791	0.00	—	3.00	Right	**3.00**[a]	848.0 [2782]	45.1 [1.78]	x-ray
2792	0.25	Down	0.50	Right	0.56	849.2 [2786]	46.8 [1.84]	x-ray
2793	2.00	Up	0.00	—	2.00	845.5 [2774]	47.1 [1.85]	x-ray
2794	0.25	Up	1.00	Right	1.03	802.5 [2633]	43.4 [1.71]	x-ray
2795	0.00	—	2.00	Right	2.00	817.2 [2681]	43.9 [1.73]	x-ray
2796	0.00	—	0.00	—	0.00	794.9 [2608]	41.0 [1.62]	x-ray
2797	0.50	Up	3.00	Left	**3.04**[a]	804.4 [2639]	42.2 [1.66]	x-ray
2798	2.00	Down	0.25	Right	2.02	751.3 [2465]	39.1 [1.54]	x-ray
2799	0.00	—	2.00	Left	2.00	744.6 [2443]	37.9 [1.49]	x-ray
2800	1.50	Up	0.00	—	1.50	754.4 [2475]	37.2 [1.54]	x-ray
2801	1.00	Down	1.00	Right	1.41	755.6 [2479]	38.4 [1.51]	x-ray
2802	0.50	Down	2.50	Left	2.55	701.6 [2303]	33.8 [1.33]	x-ray
2803	0.00	—	3.0	Left	**3.00**[a]	691.0 [2267]	32.1 [1.26]	x-ray

[a] Data point disregarded, due to excessive pitch/yaw.

Shot No.	Pitch (°)/Up or Down		Yaw (°)/Left or Right		Total Yaw (°)	Test Velocity (m/s [fps])	Measured Depth of Penetration (DOP) (mm [in])	Measurement Method
2804	0.50	Down	0.25	Left	0.56	693.4 [2275]	32.6 [1.28]	x-ray
2805	2.00	Down	0.50	Right	2.06	694.0 [2277]	32.3 [1.27]	x-ray
2806	1.00	Up	1.00	Right	1.41	616.6 [2023]	26.5 [1.05]	x-ray
2807	2.00	Up	0.50	Left	2.06	634.9 [2083]	28.7 [1.13]	x-ray
2808	0.00	—	1.50	Right	1.50	645.6 [2118]	28.7 [1.13]	x-ray
2809	0.00	—	1.00	Right	1.00	639.5 [2098]	28.5 [1.12]	x-ray
2810	2.00	Down	2.50	Right	**3.20**[a]	571.5 [1875]	24.6 [0.97]	x-ray
2811	3.00	Up	0.79	Right	**3.09**[a]	577.0 [1893]	24.6 [0.97]	x-ray
2812	2.50	Up	1.00	Left	2.69	572.7 [1879]	23.9 [0.94]	x-ray
2813	2.00	Up	0.00	—	2.00	577.9 [1896]	24.6 [0.97]	x-ray
2814	3.00	Down	1.00	Left	**3.16**[a]	517.2 [1697]	20.5 [0.81]	x-ray
2815	2.00	Down	3.00	Left	**3.61**[a]	519.7 [1705]	21.2 [0.84]	x-ray
2816	1.50	Down	1.00	Left	1.80	526.1 [1726]	22.2 [0.87]	x-ray
2817	4.50	Down	1.50	Left	**4.74**[a]	528.5 [1734]	21.5 [0.85]	x-ray
2818	2.50	Up	0.00	—	2.50	459.3 [1507]	16.6 [0.86]	x-ray
2819	0.75	Down	2.50	Right	2.61	449.0 [1473]	16.9 [0.67]	x-ray
2820	0.00	—	3.00	Right	**3.00**[a]	467.0 [1532]	18.3 [0.72]	x-ray
2821	1.50	Up	1.50	Right	2.12	458.7 [1505]	17.6 [0.69]	x-ray

[a] Data point disregarded due to excessive pitch/yaw.

Appendix B:

Ballistic Test Data - Ceramic-Faced Targets

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Shot No.	Ceramic Type	Ceramic Thickness (mm)	Areal Density (kg/m^2 [psf])	Test Velocity (m/s [fps])	Pitch (°)/ Up or Down		Yaw (°)/ Left or Right		Measurement Method	Total Yaw (°)	Measured Depth of Penetration (DOP) (mm [in])	Reference Penetration (mm)	η
2994	B_4C	1.35	3.42 [0.70]	828 [2718]	0.25	Down	2.00	Left	Cut Block	2.02	41.7 [1.64]	45.2	2.73
2997	B_4C	1.32	3.35 [0.69]	826 [2709]	0.50	Up	1.00	Right	Cut Block	1.15	39.6 [1.56]	44.9	4.18
2998	B_4C	1.30	3.29 [0.67]	**778[a] [2552]**	1.50	Up	0.25	Left	Cut Block	1.52	**36.9 [1.45]**	40.3	2.79
2999	B_4C	1.32	3.35 [0.69]	**819[a] [2687]**	3.00	Up	0.75	Right	Cut Block	**3.09[b]**	**39.4 [1.57]**	44.2	**3.55**
2845	B_4C	2.57	6.51 [1.33]	**858[a] [2814]**	0.75	Down	2.00	Right	Cut Block	2.14	**37.9 [1.49]**	48.1	4.18
2873B	B_4C	2.54	6.44 [1.32]	848 [2782]	1.50	Down	0.50	Right	Cut Block	1.58	34.3 [1.35]	47.1	5.28
2874	B_4C	2.59	6.57 [1.35]	844 [2770]	0.00	—	1.00	Right	Cut Block	1.00	32.3 [1.27]	46.8	5.85
2875	B_4C	2.57	6.51 [1.33]	847 [2779]	2.00	Down	0.50	Left	Depth Gauge	1.12	33.8 [1.33]	47.0	5.40
2846	B_4C	3.79	9.60 [1.97]	841 [2760]	3.00	Up	1.00	Left	Cut Block	2.24	8.8 [0.35]	46.5	10.39
2876	B_4C	3.81	9.67 [1.98]	846 [2774]	1.00	Down	1.00	Right	Cut Block	1.41	12.2 [0.48]	46.9	9.50
2877	B_4C	3.81	9.67 [1.98]	841 [2758]	0.00	—	1.00	Left	Depth Gauge	1.00	8.4 [0.33]	46.4	10.42
2878	B_4C	3.81	9.67 [1.98]	834 [2735]	0.50	Down	2.00	Left	Depth Gauge	2.06	10.9 [0.43]	45.7	9.53
2847	B_4C	2.08	12.89 [2.64]	840 [2757]	0.50	Down	0.00	—	NA[c]	0.50	0.0 [0.00]	46.4	9.53
3000	SiC-B	1.30	4.28 [0.88]	835 [2769]	1.00	Up	1.00	Right	Cut Block	1.41	41.2 [1.62]	45.8	2.89
3001	SiC-B	1.30	4.28 [0.88]	835 [2740]	2.00	Down	0.00	—	Cut Block	2.00	41.6 [1.64]	45.9	2.61
3002	SiC-B	1.27	4.20 [0.86]	834 [2737]	2.50	Up	0.00	—	Cut Block	2.50	40.1 [1.58]	45.8	3.55
3003	SiC-B	1.27	4.20 [0.86]	**824[a] [2704]**	2.00	Up	6.00	Right	Cut Block	**6.32[b]**	35.6 [1.40]	44.8	**5.80**
3004	SiC-B	2.59	8.57 [1.75]	835 [2740]	1.50	Down	1.50	Right	Cut Block	2.12	26.4 [1.04]	45.9	6.01
3005	SiC-B	2.59	8.57 [1.75]	843 [2767]	.050	Down	0.00	—	Cut Block	0.50	22.8 [0.90]	46.7	7.40
3006	SiC-B	2.57	8.48 [1.74]	841 [2759]	0.00	—	0.50	Left	Cut Block	0.50	30.0 [1.18]	46.4	5.14
3007	SiC-B	2.46	8.15 [1.67]	835 [2741]	0.00	—	0.50	Left	Depth Gauge	0.50	26.8 [1.06]	45.9	6.21
3009	SiC-B	3.79	12.51 [2.56]	833 [2734]	1.00	Up	1.00	Left	Cut Block	1.41	7.1 [0.28]	45.7	8.16
3042	SiC-B	3.81	12.60 [2.58]	847 [2778]	1.50	Down	1.50	Left	Cut Block	2.12	4.8 [0.19]	47.0	8.88
3043	SiC-B	3.79	12.51 [2.56]	855 [2805]	0.75	Down	2.00	Left	NA[d]	2.14	—	47.9	—
3045	SiC-B	3.84	12.68 [2.60]	843 [2765]	0.75	Down	0.50	Right	Cut Block	0.90	8.4 [0.33]	46.6	7.99
3044	SiC-B	5.08	16.80 [3.44]	851 [2791]	0.50	Down	0.00	—	NA[c]	0.50	0.0 [0.00]	47.4	7.48
3046	SiC-B	5.08	16.80 [3.44]	842 [2764]	0.00	—	0.50	Left	NA[c]	0.50	0.0 [0.00]	46.6	7.35
3047	SiC-B	5.08	16.80 [3.44]	836 [2744]	0.00	—	2.50	Right	NA[c]	2.50	0.0 [0.00]	46.0	7.25
3048	SiC-B	5.08	16.80 [3.44]	841 [2760]	1.00	Up	0.00	—	NA[c]	1.00	0.0 [0.00]	46.5	7.33

[a] Velocity outside acceptable range, 826–856 m/s (2710–2810 fps).
[b] Data point disregarded, excessive pitch/yaw.
[c] No residual DOP, penetrator defeated in ceramic tile.

Shot No.	Ceramic Type	Ceramic Thickness (mm)	Areal Density (kg/m^2 [psf])	Test Velocity (m/s [fps])	Pitch (°)/ Up or Down		Yaw (°)/ Left or Right		Measurement Method	Total Yaw (°)	Measured Depth of Penetration (DOP) (mm [in])	Reference Penetration (mm)	η
2850	Al_2O_3	1.35	4.98 [1.02]	838 [2748]	0.00	—	0.75	Left	Cut Block	0.75	42.2 [1.66]	46.1	2.05
2851	Al_2O_3	1.32	4.89 [1.00]	838 [2750]	1.00	Down	0.00	—	Cut Block	1.00	41.4 [1.63]	46.2	2.58
2852	Al_2O_3	1.35	4.98 [1.02]	842 [2762]	0.50	Down	0.00	—	NA[a]	0.50	—	46.5	—
2853	Al_2O_3	1.30	4.79 [0.98]	839 [2751]	1.00	Up	0.00	—	Cut Block	1.00	42.2 [1.66]	46.2	2.19
2854	Al_2O_3	2.59	9.59 [1.96]	839 [2754]	0.50	Up	0.50	Right	NA[a]	0.71	—	46.3	—
2855	Al_2O_3	2.49	9.21 [1.89]	835 [2740]	1.00	Up	1.00	Right	Cut Block	1.41	37.0 [1.46]	45.9	2.56
2856	Al_2O_3	2.49	9.21 [1.89]	844 [2770]	0.75	Down	1.75	Left	Cut Block	1.90	40.1 [1.58]	46.8	1.92
2857	Al_2O_3	2.59	9.59 [1.96]	839 [2754]	1.00	Up	1.00	Left	Cut Block	1.41	38.0 [1.50]	46.3	2.29
2858	Al_2O_3	3.81	14.10 [2.89]	834 [2735]	0.00	—	1.00	Right	Cut Block	1.00	21.6 [0.85]	45.7	4.53
2859	Al_2O_3	3.79	14.00 [2.87]	835 [2741]	1.00	Down	1.50	Right	Cut Block	1.80	23.8 [0.94]	45.9	4.19
2860	Al_2O_3	3.76	13.91 [2.85]	835 [2738]	0.00	—	1.25	Right	NA[a]	1.25	—	45.8	—
2861	Al_2O_3	3.76	13.91 [2.85]	837 [2745]	2.25	Up	2.00	Right	Depth Gauge	**3.01**[b]	24.1 [0.95]	46.0	**4.17**
2862	Al_2O_3	5.06	18.70 [3.83]	843 [2766]	2.00	Up	1.25	Left	Cut Block	2.36	5.6 [0.22]	46.6	5.81
2863	Al_2O_3	5.00	18.52 [3.79]	844 [2769]	0.50	Up	2.00	Right	Cut Block	2.06	8.7 [0.34]	46.7	5.45
2864	Al_2O_3	5.08	18.80 [3.85]	842 [2762]	2.00	Up	1.00	Right	Cut Block	2.24	6.1 [0.24]	46.5	5.70
2865	Al_2O_3	5.00	18.52 [3.79]	**824**[c] **[2702]**	—	—	—	—	Cut Block	**NA**[d]	8.5 [0.34]	44.7	**5.18**
2848	Al_2O_3	6.35	23.50 [4.81]	841 [2760]	0.50	Down	0.25	Left	NA[e]	0.56	0.0 [0.00]	46.5	5.24
2849	Al_2O_3	6.35	23.50 [4.81]	835 [2740]	1.00	Up	0.00	—	NA[e]	1.00	0.0 [0.00]	45.9	5.17
2888	SiC-N	3.81	12.60 [2.58]	843 [2767]	0.75	Down	0.00	—	Cut Block	0.75	6.7 [0.27]	46.7	8.40
2889	SiC-N	3.81	12.60 [2.58]	843 [2766]	1.00	Up	0.25	Left	Depth Gauge	1.03	10.2 [0.40]	46.6	7.68
2890	SiC-N	3.84	12.68 [2.60]	838 [2750]	1.00	Up	0.00	—	Cut Block	1.00	6.1 [0.24]	46.2	8.37
2891	SiC-N	3.86	12.76 [2.61]	845 [2772]	0.75	Up	1.50	Left	Depth Gauge	1.68	6.4 [0.25]	46.8	8.40

[a] Cannot obtain accurate DOP measurement.
[b] Data point disregarded, excessive pitch/yaw.
[c] Velocity outside acceptable range, 826–856 m/s (2710–2810 fps).
[d] Data point disregarded, no pitch/yaw data - x-ray failure.
[e] No residual DOP, penetrator defeated in ceramic tile.

Appendix C:

Recovered Projectile Data

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Shot No.	Ceramic Type	Ceramic Areal Density (AD) (kg/m^2)	Depth of Penetration (DOP) (mm)	Core Weight (g)	Core Condition
2994	B_4C	3.42	41.7	5.3	Tip Eroded
2997	B_4C	3.35	39.6	5.2	Tip Eroded
2998	B_4C	3.29	36.9	5.2	Tip Eroded
2999	B_4C	3.35	39.8	—	No Projectile Recovered
2845	B_4C	6.51	37.9	5.2	Tip Eroded
2873B	B_4C	6.44	34.3	5.2	Tip Fractured
2874	B_4C	6.57	32.3	—	No Projectile Recovered
2875	B_4C	6.51	33.8	5.2	Tip Eroded
2846	B_4C	9.60	8.8	3.1	Body Fractured
2876	B_4C	9.67	12.2	4.0	Tip Fractured
2877	B_4C	9.67	8.4	3.3	Body Shattered
2878	B_4C	9.67	10.9	4.0	Tip Fractured
2847	B_4C	12.89	0.0	2.1	Body Shattered
3000	SiC-B	4.28	41.2	5.2	Tip Eroded
3001	SiC-B	4.28	41.6	—	No Projectile Recovered
3002	SiC-B	4.20	40.1	—	No Projectile Recovered
3003	SiC-B	4.20	35.6	—	No Projectile Recovered
3004	SiC-B	8.57	26.4	5.1	Tip Fractured
3005	SiC-B	8.57	22.8	4.9	Tip Fractured
3006	SiC-B	8.48	30.0	—	No Projectile Recovered
3007	SiC-B	8.15	26.8	—	No Projectile Recovered
3009	SiC-B	12.51	7.1	3.3	Body Fractured
3042	SiC-B	12.60	4.7	2.6	Body Fractured
3043	SiC-B	12.51	—	3.9	Body Shattered
3045	SiC-B	12.68	8.4	2.4	Body Shattered
3044	SiC-B	16.80	0.0	2.5	Body Shattered
3046	SiC-B	16.80	0.0	1.9	Body Fractured
3047	SiC-B	16.80	0.0	1.6	Body Shattered
3048	SiC-B	16.80	0.0	2.0	Body Fractured
2850	Al_2O_3	4.98	42.2	—	No Projectile Recovered
2851	Al_2O_3	4.89	41.4	5.2	Tip Eroded
2852	Al_2O_3	4.98	—	—	No Projectile Recovered
2853	Al_2O_3	4.79	42.2	5.3	Tip Eroded
2854	Al_2O_3	9.59	—	—	No Projectile Recovered
2855	Al_2O_3	9.21	37.0	5.2	Tip Eroded
2856	Al_2O_3	9.21	40.0	5.2	Tip Eroded
2857	Al_2O_3	9.59	38.0	5.2	Tip Eroded
2858	Al_2O_3	14.10	21.6	5.0	Tip Fractured
2859	Al_2O_3	14.00	23.8	5.0	Tip Fractured

Shot No.	Ceramic Type	Ceramic Areal Density (AD) (kg/m^2)	Depth of Penetration (DOP) (mm)	Core Weight (g)	Core Condition
2860	Al_2O_3	13.91	—	4.6	Tip Fractured
2861	Al_2O_3	13.91	24.1	5.1	Tip Fractured
2862	Al_2O_3	18.70	5.6	2.7	Body Fractured
2863	Al_2O_3	18.52	8.7	4.0	Tip Fractured
2864	Al_2O_3	18.80	6.1	2.6	Body Shattered
2865	Al_2O_3	18.52	8.5	4.4	Tip Fractured
2848	Al_2O_3	23.50	0.0	1.8	Body Shattered
2849	Al_2O_3	23.50	0.0	1.6	Body Fractured
2888	SiC-N	12.60	6.7	3.6	Body Fractured
2889	SiC-N	12.60	10.2	4.1	Body Shattered
2890	SiC-N	12.68	6.1	3.2	Body Shattered
2891	SiC-N	12.76	6.4	3.3	Body Fractured

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The depth of penetration (DOP) or thick-backing technique allows the ballistic evaluation and ranking of armor ceramics independent of armor configuration. The test projectile is fired into a ceramic tile backed by a semi-infinite block. The residual penetration into the backing material is measured and compared to the penetration of the projectile into a monolithic block of the backing material. This report adapts this technique to evaluate armor ceramics for personnel protection using the caliber .30 armor-piercing M2 (APM2) and armor-grade aluminum alloy 5083 (Al 5083), MIL-A-46027, as the backing material.

Penetration of the APM2 into monolithic Al 5083 was determined over a range of velocities. Several thicknesses of boron carbide (B4C), silicon carbide (SiC), and aluminum oxide (Al2O3) were tested to determine ballistic performance as a function of ceramic areal density. Projectile cores were recovered and analyzed. Postmortem condition of the cores was correlated to DOP results.

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